Conifer Crown Fuel Modeling: Current Limits and Potential for Improvement

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ABSTRACT

The characterization of crown fuel parameters is a critical element in many fire behavior simulators used for decision support in the fire-prone coniferous forests of western North America. We briefly review the development and limitations of current conifer crown fuel models in this region as they impact the potential utility of fire behavior simulations. We then identify and evaluate conifer crown modeling efforts and techniques that have been advanced outside the fire and fuels domain, including models developed for bio-energy and carbon inventory, wood quality determination, and empirical and process-based growth and yield projections. Whereas the latter models often focus on crown parameters distinct from those traditionally described in fuels studies, we contend that advances in conifer crown fuel modeling can be made by recognizing and extending the results of these parallel lines of research. Such advances are needed to adequately parameterize crown fuels if we are to reap advantages from next-generation fire behavior models and, by extension, to improve our understanding of fuels management and treatment strategies. At the same time, more information must be derived from long-term fuels treatment and silvicultural trials to improve our understanding of how conifer crowns respond to treatments.

Keywords: crown fuels, crown biomass, crown architecture, process-based models, wildland fire

Throughout the forested landscapes of western North America, the total amount and spatial distribution of crown fuels are important determinants of wildfire behavior. The relationship of forest stand structure to fire behavior has been articulated on a theoretical basis (van Wagner 1977, Alexander 1988, Agee 1996, Scott and Reinhardt 2001), investigated in simulation modeling studies (van Wagtendonk 1996, Scott 1998a, Stephens 1998, Parsons et al. 2011), and demonstrated empirically in observations of fire behavior in recently-treated stands (Omi and Martinson 2002, Pollet and Omi 2002, Agee and Skinner 2005). This body of evidence forms the basis for altering fire behavior by modifying forest structure and has resulted in the refinement and widespread adoption of fuel-reduction thinnings that aim to alter crown fire potential by establishing canopy fuel structures that are resistant to crown fire initiation and spread (Graham et al. 1999, 2004, Keyes and O'Hara 2002). Fire behavior simulation software applications are the primary planning tools used by managers to compare the anticipated effects of fuels treatment alternatives (McHugh 2006), but their utility remains limited by the accuracy with which the horizontal and vertical structure of canopy fuels can be characterized. With this paper, we review the state of knowledge regarding crown fuel modeling, highlight its primary limitations, and discuss opportunities for advancing this field by incorporating the substantial body of research on tree crown architecture that has developed in allied disciplines.

Current Status of Crown Fuel Modeling

Characterizations of wildfire hazard based on crown conditions have been in use by fire managers of the West for decades. The earliest characterizations, such as Fahnestock's (1970) dichotomous keys, were categorical, enabling fire managers to estimate potential crown fire behavior in stands of various generalized crown and canopy conditions. With the introduction of van Wagner's (1977) empirical crown fire initiation and spread equations, crown fire hazard could be quantified and made more closely representative of local conditions with site-explicit stand, surface fuel, and environmental input parameters. The rising demand to alter potential fire behavior via active manipulation of crown fuels (Stephens 1998, Keyes and O'Hara 2002) resulted in the modification of these fire behavior equations for their deployment in numerous software applications (Scott 1999, Reinhardt and Crookston 2003, Carlton 2006, Lutes 2006).

For fire and fuels managers, defining the appropriate model input assignments for these powerful fire behavior applications presents many challenges. Prominent among these is the calculation of canopy and crown attributes and their rendering into two critical model input parameters: canopy base height (CBH) and canopy bulk density (CBD). Early studies of relevance to these concerns were in the prediction of slash weights and fuel load distributions, such as Brown's (1978) mechanical study of weights and bulk densities of western trees, where allometric relationships of CBH and CBD to tree measurements (dbh, crown length, tree height, and live crown ratio) were determined. At the stand level, crown recession analyses, such as those conducted by McAlpine and Hobbs (1994), have attempted to relate planting density to crown fire initiation potential in plantations. But this approach only indirectly addresses the problem of quantifying CBH and CBD as model inputs.

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Research from the wildland fire community during the past decade has targeted this area of decision support for advancement (e.g., Scott and Reinhardt 2001, Cruz et al. 2003, Keane et al. 2005). The need for better stand-level estimates of CBH and CBD prompted plot-scale intensive deconstruction of tree crowns of five western species (Reinhardt et al. 2006). That work resulted in the development of correlative relationships (Keane et al. 2005) and presumably better decision support tools (Scott and Reinhardt 2005) for managers assigning values for those parameters in fire and fuels planning software. Based on this and earlier work, crown fuel attributes are now calculated by managers with few exceptions via single-tree allometries applied to standard forest inventory plot data, most typically by using the Fire and Fuels Extension of the Forest Vegetation Simulator (FVS-FFE; Reinhardt and Crookston 2003).

Yet, the intensive methodology applied by Reinhardt et al. (2006) did not permit analysis of crown and canopy features for stands of varying structures or treatment histories. Major weaknesses were exposed in employing FVS-FFE's existing CBD and CBH algorithms in the Black Hills of South Dakota (Keyser and Smith 2010). Keyser and Smith demonstrated clearly that better models of crown fuels that include more accurate representations of vertical structure and that accommodate variations in local site and stand conditions (e.g., density and structure) are needed. Similarly, using Keyser and Smith's Black Hills data, Cruz and Alexander (2012) found that, whereas the stand-level CBH and canopy fuel load models of Cruz et al. (2003) performed reasonably well, alternative approaches were needed to estimate CBD. Overall, it is apparent that improved models of crown and canopy characteristics are needed. These models would enable managers to more efficiently plan fuels treatments and evaluate their impacts on potential fire behavior at the project level.

More recently developed mechanistic models of fire spread, such as the Wildland Urban Interface Fire Dynamics Simulator (WFDS; Mell et al. 2009) and FIRETEC (Linn et al. 2002), also require detailed characterizations of crown fuels. Linn et al. (2005) and Mell et al. (2009) applied these physics-based models of fire spread to stands simulated using geometric models of crown volume (e.g., parabolic and conic forms) and simplified models of crown bulk density; both studies found that simulated fire behavior was sensitive to crown and canopy characteristics. Adopting a more complex model of crown structure capable of describing within- and among-tree heterogeneity, Parsons et al. (2011) clearly demonstrated that the characterization of crown fuels could materially alter the simulated fire behavior in these systems.

Looking beyond static models of crown fuels, silvicultural treatment effects on fuel characteristics have been simulated but not observed. In a rare study of temporal changes to crown fuel characteristics, Scott and Reinhardt (2007) used FVS-FFE to simulate the effect of various treatments on crown fuels. Yet, we are aware of no long-term study of actual treatment effects on observed crown fuel characteristics that has been conducted to date. Such a study would enable a validation test of modeling simulations.

A related yet often overlooked relation of crown fuel condition to crown fire potential is the moisture content of foliage. In combination with canopy base height, foliar moisture content (FMC) determines the potential for canopy ignition (van Wagner 1977). Its effect is minor relative to canopy base height (Scott 1998b) but is an operationally significant factor in crown fire resistance, and its proportional importance is positively related to surface fire intensity (Keyes and O'Hara 2002). Studies of the FMC of numerous North American species have been published (Agee et al. 2002, Keyes 2006), in some cases reporting seasonal variations and differences between new and older foliage, and are useful to managers for assigning generalized FMC values in fire model simulations. The effects of silvicultural treatments on FMC are unknown, however, as apparently no studies of treatment response have been conducted for any North American tree species (Keyes 2006). Identification of treatment effects on FMC are necessary to determine whether changes in FMC occur, and if so, whether they offset or exacerbate changes to crown fuel characteristics (CBD and CBH) associated with hazard fuels treatment.

Utility of Crown Models from Other Fields

Outside of the fire and fuels domain, extensive study has been made of the architecture of conifer crowns, owing to their importance as bioenergy and carbon stocks, determinants of wood quality, and drivers of tree and stand growth. Various lines of research have investigated conifer crown structural relationships at resolutions ranging from whole-tree biomass allometries to three-dimensional distributions of individual crown components (e.g., foliage or live branches). Although distinct crown components traditionally have been studied at disparate levels of resolution in different fields, recent work has been both more attentive to developments in other disciplines and increasingly concerned with the vertical structure of the crown. There remains, however, comparatively little information concerning the magnitude of intrinsic variation in crown architecture or on the effects of stand manipulations (but see, e.g., Brix 1981; Garber and Maguire 2005a, 2005b)

In the 1970s, increased use of whole-tree harvesting techniques coupled with higher fossil fuel energy prices initiated widespread efforts to quantify crown biomass relationships. Weight scaling of merchantable timber or pulpwood had been in use in many parts of North America prior to this time but there had been relatively little interest in branch wood and foliage biomass. Crown biomass regression equations were soon developed for many conifer species across the United States and Canada (e.g., Young et al. 1980, Tritton and Hornbeck 1982, Evert 1985, Standish et al. 1985). Methodology varied, but the studies producing these equations had aims similar to those of Brown (1978) in seeking regional allometries for estimating total crown mass of individual trees from standard forest inventory measurements. Recently, with growing interest in forest carbon inventory, many of the results and data sets from this class of tree biomass studies have been revisited in meta-analytic studies aiming to develop carbon yield equations for application at national or continental scales (see, e.g., Jenkins et al. 2003, Wirth et al. 2004).

Many existing crown biomass equations are of limited utility for canopy fuels modeling. Most biomass studies report separate foliage and branch wood biomass equations, but in relatively few instances is branch wood disaggregated by fuel time lag class or by live/dead status. The spatial distribution of biomass within crowns is also generally ignored, although more intensive harvesting methods are now occasioning the need for information on the vertical distribution of branch wood biomass in some regions (e.g., Tahvanainen and Forss 2008). Nonetheless, this body of research on conifer biomass allometries provides considerable information about how crown components vary systematically with tree attributes. Broadly, it is apparent that differences in dbh account for an appreciable proportion of the variation in total crown biomass. At the same time, utilizing additional information on tree height and crown length (or crown ratio) can materially improve the accuracy of crown biomass equations (see, e.g., Brown 1978, Evert 1985). Less information is provided concerning the conditioning effects of stand attributes. In particular, few studies examine the influence of stand density on individual tree foliage or branch wood biomass after having accounted for its concomitant effects on tree-level attributes, such as crown length.

Whereas most tree biomass studies have focused on characterizing total crown weights, much more detailed representations of conifer crowns have been developed for stem wood quality assessment. Lumber grade and product recovery are strongly influenced by branch size and longevity, particularly by maximum branch diameter and branch density on the lower bole. Consequently, for a number of commercially important conifer species, the vertical distribution of branch basal area has been thoroughly examined (e.g., Colin and Houllier 1992, Maguire et al. 1994, 1999). Characteristic products of this line of research are systems of equations to jointly predict branch basal diameter distributions and numbers of branches along the bole as a function of tree dimensions, such as dbh, total height, and crown length. Some of the highest resolution branching models have been developed for pine plantations in the southern United States. Recent work by Trincado and Burkhart (2009), for example, characterizes not only the vertical distribution of loblolly pine (*Pinus taeda*) branch diameters but also branch orientation (i.e., azimuth) as well as branch survivorship and retention.

Models of conifer branching structures have considerable potential for crown fuel modeling but presently exist for relatively few species. Developing similarly detailed models for other species and for conifers growing in stands under less intensive management regimes would require further investments in data collection. Regardless, the existing body of work has advanced highly flexible and statistically efficient modeling techniques for characterizing simultaneously the size and spatial distributions of branches within the crown. These technical contributions should not be overlooked because they improve not only the ability to credibly simulate crown structure but also the ability to identify elements of that structure in empirical data. For example, this line of research has shown a tendency in several conifer species for branch diameters to peak not at crown base but rather within the lower-third of the live crown (Colin and Houllier 1992, Kershaw and Maguire 1995, Maguire et al. 1999, Weiskittel et al. 2010). This peaking behavior became more apparent as profile models of maximum branch diameter evolved (e.g., Maguire et al. 1999) and in turn stimulated the development of more flexible mathematical descriptions capable of capturing this feature of the vertical distribution of branch cross-sectional area.

As wood quality is affected most directly by branch basal diameters, many studies of branching structure do not report on branch biomass or on the distribution of foliage—parameters needed for crown fuel modeling. However, predictive models of conifer branch diameters can be readily extended to characterize crown biomass distributions because of strong relationships between, on the one hand, branch wood or foliage biomass and, on the other hand, primary branch basal area and crown position (see, e.g., Kershaw and Maguire 1995, Gilmore and Seymour 1997, Monserud and Marshall 1999). Another consideration in the application of branch diameter distribution models for crown fuel characterization is the need for fractionation of branch wood into time lag or diameter size classes. This would necessitate the use of individual branch taper models, along the lines of those developed by Weiskittel and Maguire (2006) for Douglas-fir (*Pseudotsuga menziesii*) but extended to incorporate higher-order branching.

Shifting the focus from direct characterizations of branch mass or cross-sectional area distributions, other studies have sought to describe the overall geometry or form of conifer crowns. Early work along these lines used paraboloid models to describe foliar and crown volumes (e.g., Mitchell 1975, Biging and Wensel 1990). More recently, flexible nonparameteric (Doruska and Mays 1998) and stochastic (Gill and Biging 2002) crown profile modeling strategies have been advanced. One of the primary motivations for modeling crown geometry has been to better characterize tree competition via crown overlap metrics. As such, these models and modeling strategies may have direct applications in describing fuel connectivity within stands, as would modeling efforts that have focused on crown radius (e.g., Gill et al. 2000) and height to crown base (Ritchie and Hann 1987). However, additional information would be needed to infer within-crown fuel distributions from the geometry. In particular, the geometric approach makes no distinction among crown components (foliage or branch wood) and the conversion from volume to mass requires detailed information on vertical and horizontal variations in crown bulk density (e.g., Linn et al. 2005).

Foliar area and foliar mass distributions have been of most direct interest in investigations focused on tree and stand growth. Foliar area is an important determinant of tree volume increment, and the foliage profile directly impacts radial wood increment along the bole (Kershaw and Maguire 2000). In part to parameterize these effects for tree growth simulation, detailed foliage distribution models have been developed for commercially important conifer species (e.g., Maguire and Bennett 1996, Xu and Harrington 1998, Weiskittel et al. 2009). Similar to the approach of Keyser and Smith (2010), these modeling efforts typically describe the vertical profiles of foliar mass and/or area using parametric distributions like the Weibull or beta. The parameters of these distributions have been usefully indexed against tree attributes, such as breast-height diameter, total height, and canopy position, but there is less (and contradictory) evidence regarding the utility of stand-level characteristics as predictors (see Garber and Maguire 2005a, Weiskittel et al. 2009).

It is notable that many recent efforts aimed at characterizing vertical foliage distributions are motivated by a growing interest in the development of process-based growth and yield models. Process-based growth models are commonly based on functional relationships between sapwood cross-sectional area and foliage mass or area. In particular, the pipe model theory of Shinozaki et al. (1964) has prompted theoretical (Mäkelä and Valentine 2006) and empirical (Maguire and Batista 1996; Schneider et al. 2008) research on foliar mass and its vertical distribution. This is a promising approach for robust modeling of crown fuels. To the extent that it is possible to employ ecophysiological principles to condition crown modeling efforts and model forms, these principles potentially offer a means to achieve credible models with smaller data sets, while maintaining sound allometric constraints among estimates of crown components.

Discussion and Recommendations

Extensive crown research advanced outside of the fire science domain offers much potential to inform the further development of canopy fuel models. Limiting the direct application of much of that research are the facts that (1) studies of the vertical structure of crown biomass have often focused primarily on the foliage or on the branch wood components, rarely both; and (2) the time lag size classes traditionally employed for branch wood in fuels studies are not commonly differentiated in other fields. Nonetheless, for many conifer species, there appear to be consistent biophysical constraints on branch wood and foliage allocation patterns. These constraints effect strong empirical relationships—particularly at the branch level—that could facilitate the integration of previously documented foliage and branch wood relationships. Tying these relationships together is necessary for the development of credible models of fuels components and their vertical distribution along the bole. Compared to vertical structure, there has been much less work on the horizontal (i.e., radial) distribution of foliage and fine branch masses around the stem (but see Kershaw and Maguire 1996 and references therein). However, improved branch basal diameter distribution models coupled with recent research on branch taper comprise a promising path toward the development of more accurate models of the three-dimensional fine fuels structure of individual crowns.

Advancements in the accuracy and resolution of individual crown models are needed to better inform fuels management and fire behavior simulations. Yet, the impact of improved crown-level models will critically depend on how the resultant information is aggregated and summarized for fuels modeling. In particular, more detailed crown-level information could be superfluous to the calculation of CBH and CBD statistics. At the same time, improved crown models could provide essential information on within-stand variation in canopy height, density, and connectivity—variation that is both ubiquitous and significant in terms of potential fire behavior. An important component of this variation in canopy depth and density is captured by models sensitive to the conditioning effects of tree species, size, and crown length on mean crown dimensions. There will remain, however, considerable within-stand variation and modeling uncertainty attributable to individual trees' deviations from conditional mean crown dimensions. Crown modeling efforts to date have focused almost exclusively on species- and size-dependent means. With the exception of the studies by Gill and Biging (2002) and Parsons et al. (2011), there have been few efforts to quantify and integrate intrinsic variation into crown simulation models, as has been done in other forest modeling applications (e.g., Stage and Wykoff 1993).

Managers are increasingly expanding their planning analysis beyond immediate posttreatment effects to include analysis of the persistence of alternative fuel treatment effects. Although not currently substantiated by existing research, a physiological perspective of posttreatment crown dynamics (density and quality of foliar fuels, rates of crown expansion and ascension) suggests that fuel treatments will vary not only in immediate posttreatment fire hazard but in the trajectories of crown fuel structures that develop in the years and decades that follow treatment. Such analysis needs are bound to further demonstrate the limitations of existing crown fuel models and the need for quantitative models that characterize the quantity and distribution of crown fuels over space and time. For relatively small investments, the long-term maintenance and remeasurement of previously established fuels reduction or other silvicultural trials (e.g., thinning, levels of growing stock trials) could provide valuable information on posttreatment crown dynamics and the accuracy with which the crowns are characterized by present generation fuels models.

The problem of better characterizing crown fuel loads in space and time is an urgent one. The current quality of crown fuel modeling efforts has been demonstrated to be inadequate in meeting the needs of empirical fire behavior simulation models (Cruz and Alexander 2010). This limitation will be felt even more acutely as emerging computational fluid dynamics models of fire spread, such as WFDS and FIRETEC, become operational. These next-generation fire models are data-intensive and sensitive to highly specific information about the spatial distribution of forest fuels (Linn et al. 2005, Mell et al. 2009, Parsons et al. 2011). The accuracy of projections from those fire models will be largely constrained by the quality of input value assignments.

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